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EVALUATION OF CEMENT MORTARS BY ULTRASOUND

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ABSTRACT

Most of the concrete properties are affected by the cement and the mechanical as well as some durability properties of cements are determined through cement mortars. However, applications of ultrasound on determining the properties of cement mortars are quite limited. Therefore, the required specimen dimensions, transducer frequencies have not yet been established for cement mortars. In this study, ultrasonic pulse velocity (UPV) of mortars was determined with different transducers of different frequencies for different size and shape of specimens and the relations between UPV and various properties of cement mortars were investigated. Within the scope of the experimental program, three different ultrasonic frequencies (54, 82, and 150 kHz) were utilized. For this purpose, mortar mixtures were prepared with various water-to-cement ratios having a constant cement content of 500 kg/m^3. From each mortar mixture, cubical and prismatic specimens of various sizes were prepared. It was concluded that when the effect of specimen geometry on the UPV of mortars were considered, as the path length increases there is a significant reduction in the measured UPV, and when the length/wavelength ratio increases, the measured UPV with different transducer frequencies tends to converge to a single value. It was also observed that the linear relationship that exists between the compressive strength and UPV varies, as the age of mortar increases.

Keywords: Ultrasonic pulse velocity, cement mortar, testing frequency, specimen size and shape.

1. INTRODUCTION

The mechanical properties of a material can be determined through destructive or nondestructive testing methods. In destructive testing, the material being tested is permanently altered or deformed and the test can be performed only once on the same material. Therefore, many test substrates are needed through destructive testing to obtain a convenient measure. On the other hand, a nondestructive test can be performed over and over on the same material without negative impact on the material itself, and also the future usefulness of the material is not affected [1, 2].

Ultrasonic inspection has been used on concrete since the end of 1940s with ultrasonic pulse velocity (UPV) being the most widely used parameter [3]. Main UPV applications in concrete can be categorized as, determining uniformity, determination of dynamic (pulse) modulus of elasticity, strength estimation, determining hardening characteristics, durability assessment, crack detection, appraisal of the effect of fire exposure, and establishing an acceptance criteria [1, 2, 4]. Therefore, the related parameters of testing such as the transducer frequency, the specimen geometry and etc. are well-known. For example, the transducers utilized for testing concrete are narrowband transducers with a central frequency of about 50 kHz. These, rather lower frequency transducers are needed for concrete because the aggregate particles in concrete act as impurities, which will cause the dispersion of acoustic waves of higher frequencies. On the other hand, most of the concrete properties are affected by the cement and the mechanical as well as some durability properties of cements are determined through cement mortars. However, applications of ultrasound on determining the properties of cement mortars are quite limited. Therefore, the required specimen dimensions, necessary transducer frequencies have not yet been established for cement mortars.

The objective of this study was to determine the ultrasonic pulse velocity of cement mortars, to investigate the relationship between the UPV of cement mortars and their strength characteristics as evaluated during destructive testing at different ages and to make an attempt to evaluate the effects of different specimen size and shape on ultrasonic pulse velocity. A total of five mortar mixes were prepared with ten different water-to-cement (w/c) ratios with constant cement content. From each mortar mixture, cubical and prismatic specimens were prepared. On these specimens UPV was determined using all possible dimensions using 54, 82 and 150 kHz transducers. In addition, compressive strengths of cement mortars were also determined.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The portland cement used in this study was produced according to the European Standards EN-197/1 and labeled as CEM I/42.5 N. The fine aggregate was river sand with a specific gravity of 2.41. The gradation of the fine aggregate was also determined by sieve analysis.

2.2 Mixture proportions

Within the scope of the experimental program, five cement mortar mixtures were prepared. All of the mixtures had a cement content of 500 kg and the w/c ratios were changed from 0.40 to 0.60 with increments of 0.05. The mixture design of the cement mortars is presented in Table 1.

Table 1. Mixture Design

Mix Number	w/c	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)
1	0.40	200	500	1525
2	0.45	225	500	1441
3	0.50	250	500	1380
4	0.55	275	500	1332
5	0.60	300	500	1284

2.3 Preparation and casting

The mixing process for all the mixtures was kept constant. It started by mixing all the cement and sand for a minute using a standard mixer described by ASTM C109/C 109M-01. Then three quarters of the mixing water was added and mixed for an extra minute. Later on, remaining water was added and the mortar was mixed for an additional two minutes.

After the mixing was completed, 50-mm cubic specimens and prismatic specimens having dimensions of 4x4x16 and 7x7x32 cm were prepared from each mortar mixture. The 50-mm cubes were used for compressive strength as specified by ASTM C109/C and ultrasonic pulse velocity (UPV) tests. The prismatic specimens were used to determine the flexural and compressive strength as specified by TS EN 196-1 and UPV tests. After demolding, all specimens were immersed in water at approximately 21 °C.

2.4 Testing

The compressive strength of 5-cm cubical specimens and 4-cm prismatic specimens were determined at 2, 7 and 28 days of mortar age using a universal testing machine. The test procedure for cubic and prismatic cement mortar specimens were in accordance with ASTM C109/C and TS/EN 196-1, respectively. The mean value of six specimen strengths at a particular age was considered as the compressive strength.

The UPV testing described in ASTM C597-97 was performed on six specimens at 2, 7, and 28 days. The testing system consists of a pulser-receiver unit with a built-in data acquisition system and two transducers. Three different transducers with 54 kHz, 82 kHz, and 150 kHz central frequencies were used. Through transmission UPV measurements were conducted with the transducers firmly coupled to the opposite ends of the specimens using petroleum jelly as the couplant between the transducer and the specimen. Through transmission UPV test gives the acquired the pulse arrival time which describes the elapsed time between the time of pulse application and arrival on the opposite face of the specimen. UPV was calculated by dividing the path length to the pulse arrival time.

3. RESULTS AND DISCUSSIONS

Table 2 presents the mean compressive strength of cubic specimens at 2, 7, and 28 days, together with its coefficient of variation from the results of six specimens. As expected, the compressive strengths generally decreased with increasing w/c ratios. Few of the mixtures with lower w/c showed also a reduction in compressive strength, which was related with the compaction problems of these stiff mixtures.

Table 2. Compressive Strength of Cement Mortar Mixtures

Test Age	Specimen Size (cm)	w/c				
		0.40	0.45	0.50	0.55	0.60
		Compressive Strength (MPa)				
2 days	**4x4x4**	24.5 [14][*]	26.9 [12]	21.9 [10]	18.2 [9]	14.5 [9]
	5x5x5	26.2 [5]	26.4 [6]	21.8 [5]	17.3 [10]	15.5 [9]
7 days	**4x4x4**	36.4 [9]	33.8 [9]	30.8 [11]	27.2 [8]	19.9 [8]
	5x5x5	32.2 [15]	37.9 [7]	38.0 [2]	27.6 [8]	24.7 [9]
28 days	**4x4x4**	42.4 [5]	44.2 [7]	39.8 [7]	34.4 [8]	34.2 [8]
	5x5x5	43.2 [4]	48.4 [6]	43.2 [10]	34.9 [3]	32.2 [13]

[*] Number in parenthesis is the coefficient of variation in percent

The mean UPV of all the specimens for 54 kHz, 82 kHz, and 150 kHz at 2, 7, and 28 days and coefficient of variations of UPV were also measured. Table 3 presents these values obtained for 150 kHz. The effect of specimen geometry on UPV is investigated using the values in this Table. As an example, Figure 1 presents the UPV test results obtained at 28 days with 150 kHz frequency transducers with changing path length. As seen from this sample figure, the

UPV decreases when the measurement length increases at all w/c ratios. The decrease in pulse velocity is attributed to the attenuation which is the loss of the wave energy as it propagates through the medium [2, 5]. All of the UPV test results can be compiled as shown in Figure 2. In this figure the UPV measurements with a measurement length of 4 cm in x-axis is compared with all the other measurement lengths in y-axis for 2, 7 and 28 day measurements with 150 kHz frequency transducers. As seen from this figure, there is a constant decrease in the slope of the lines when the measurement length is increased.

Table 3. UPV of Prismatic and Cubical Specimens for 150 kHz

Test Age	Path Length (cm)	w/c									
		0.40		0.45		0.50		0.55		0.60	
		UPV (m/s) 54 kHz									
2 days	4	4608	[2.0]	4361	[0.5]	4180	[2.2]	3947	[0.7]	3714	[0.5]
	5	4561	[1.9]	4279	[1.2]	4090	[1.4]	3838	[0.8]	3622	[0.7]
	7	4407	[1.1]	4144	[0.9]	3922	[0.4]	3774	[0.9]	3594	[0.5]
	16	4185	[0.4]	3744	[0.3]	3675	[0.3]	3598	[0.4]	3491	[0.1]
	32	4090	[0.1]	3915	[0.3]	3804	[0.1]	3598	[0.3]	3458	[0.1]
7 days	4	5033	[1.4]	4752	[0.1]	4541	[0.6]	4350	[0.5]	4157	[0.4]
	5	4973	[1.2]	4532	[0.9]	4317	[0.8]	4158	[0.7]	3960	[0.6]
	7	4688	[0.7]	4431	[0.1]	4311	[0.8]	4129	[0.3]	3979	[0.6]
	16	4457	[0.2]	4219	[0.7]	4133	[0.1]	3971	[0.5]	3872	[0.3]
	32	4375	[0.1]	4183	[0.4]	4091	[0.3]	3953	[0.1]	3814	[0.1]
28 days	4	5483	[0.7]	5264	[0.7]	4975	[1.2]	4645	[0.5]	4431	[0.9]
	5	5290	[1.2]	4981	[1.0]	4695	[0.6]	4433	[0.7]	4371	[1.1]
	7	4910	[1.1]	4666	[0.2]	4539	[0.5]	4387	[0.2]	4271	[0.6]
	16	4634	[0.3]	4479	[0.2]	4374	[0.2]	4232	[0.4]	4128	[0.3]
	32	4547	[0.1]	4367	[0.1]	4279	[0.1]	4185	[0.1]	4103	[0.1]

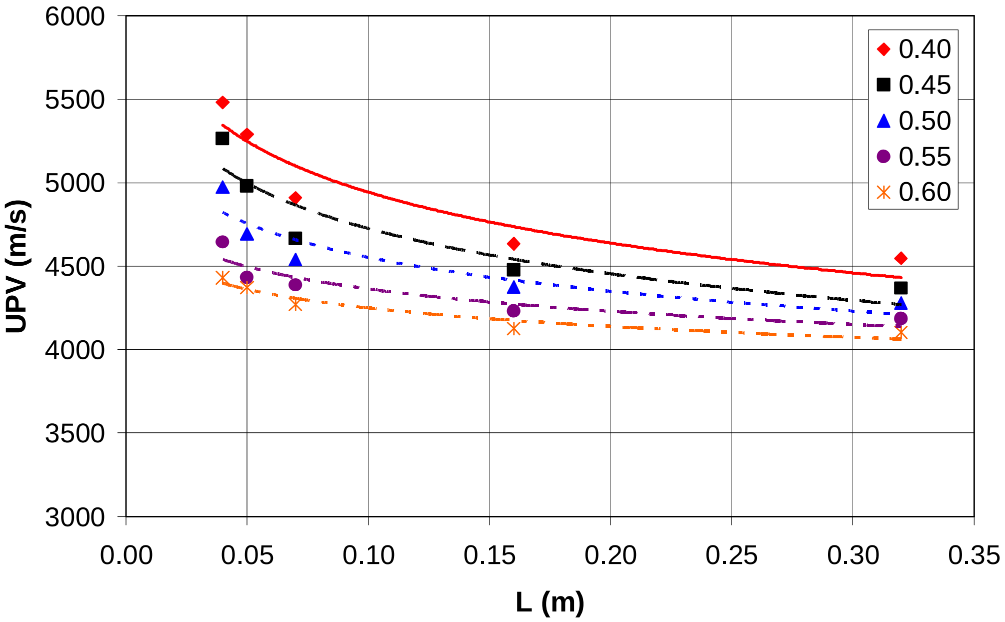


Figure 1. The Relationship between UPV and Measurement Length

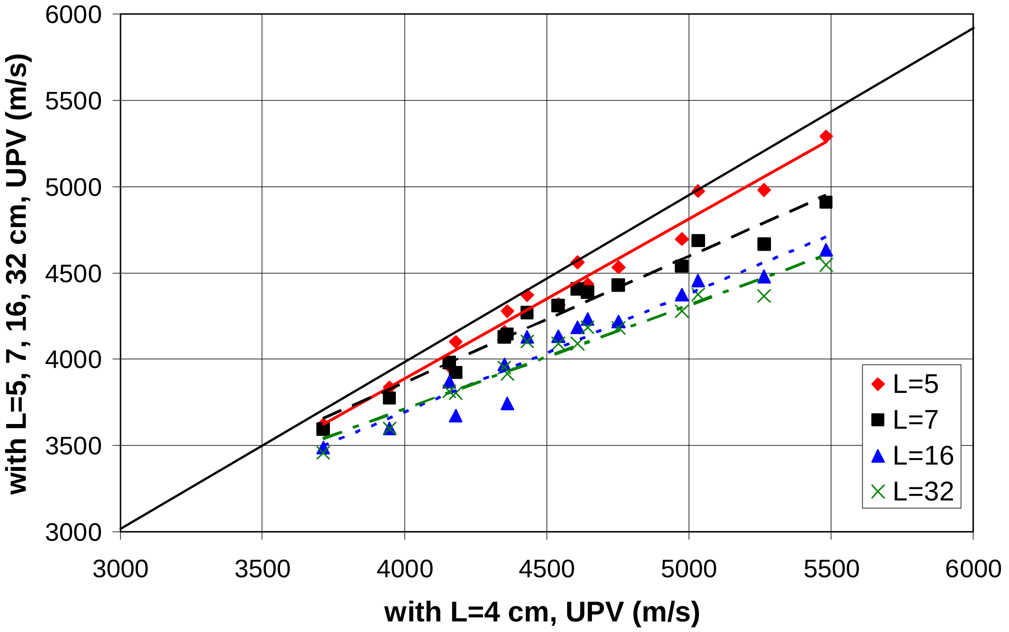
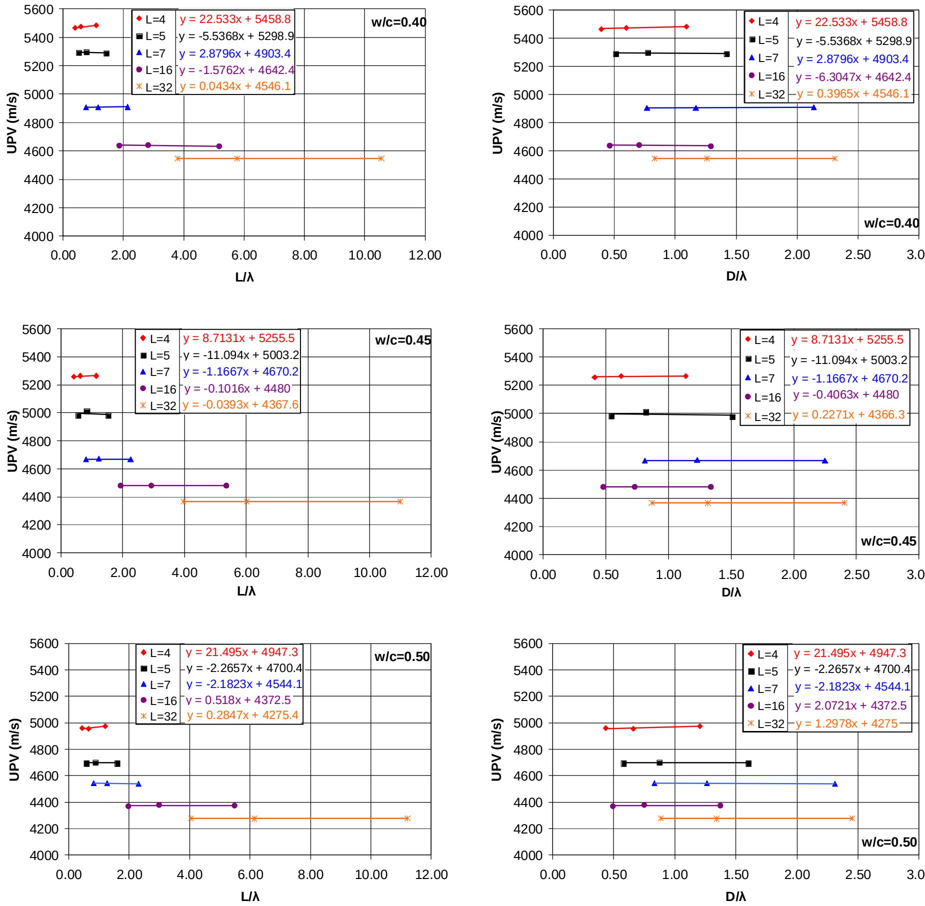


Figure 2. Reduction in UPV with Changing Measurement Length

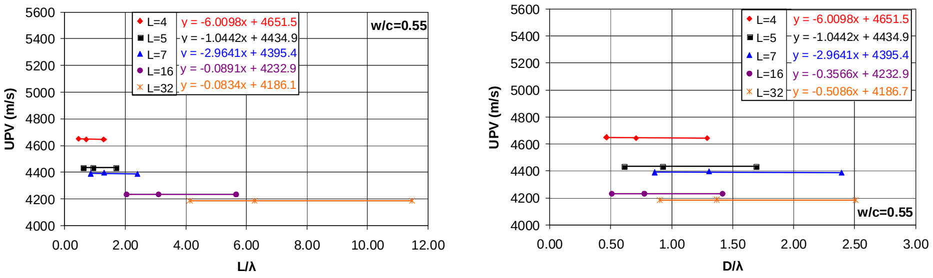
In several standards there is conflicting information on the effects of transducer frequency on UPV. For example in the standard test method described for rocks, ASTM D 2845, it is stated that the frequency of the transducers and the minimum lateral dimension of the specimen may affect the UPV test results. Therefore, it is recommended that the minimum lateral dimension of the test specimen should be at least five times greater than the wavelength of the traversed wave, and also recommended that the wavelength should be at least three times greater than the average grain size [6]. However, when the standard test method for concrete, ASTM C 597, is examined, a requirement of the least dimension of the test object exceeding the wavelength of the ultrasonic vibrations is provided. Moreover, it is also stated in the standard that the pulse velocity is independent of the dimensions of the test object provided that the reflected waves from boundaries do not complicate the determination of the arrival time of the directly transmitted pulse [7]. To investigate the effect of transducer frequency and specimen geometry on the measured UPV of cement mortars, the test results are presented with respect to the length/wavelength (L/λ) and width/wavelength (D/λ) as shown in Figure 3(a) and 3(b), respectively. As seen from Figure 3(a), as the L/λ increases, measurement of UPV with three different transducers yields similar UPV results for each specimen length considered. For a L/λ smaller than one, the slope of the fitted line increases which shows a higher variation in the measured UPV obtained from three different transducer frequencies.



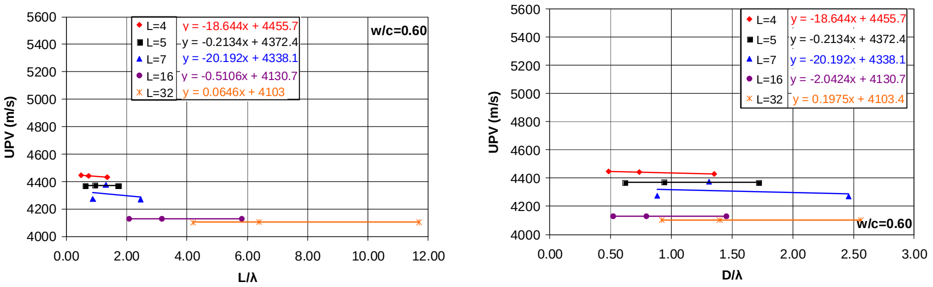
a) w/c=0.40
L/λ, D/λ

b) w/c=0.45
L/λ, D/λ

c) w/c=0.50
L/λ, D/λ



d) w/c=0.55
L/λ, D/λ



e) w/c=0.60
L/λ, D/λ

Figure 3. Effect of Testing Frequency and Specimen Geometry on UPV

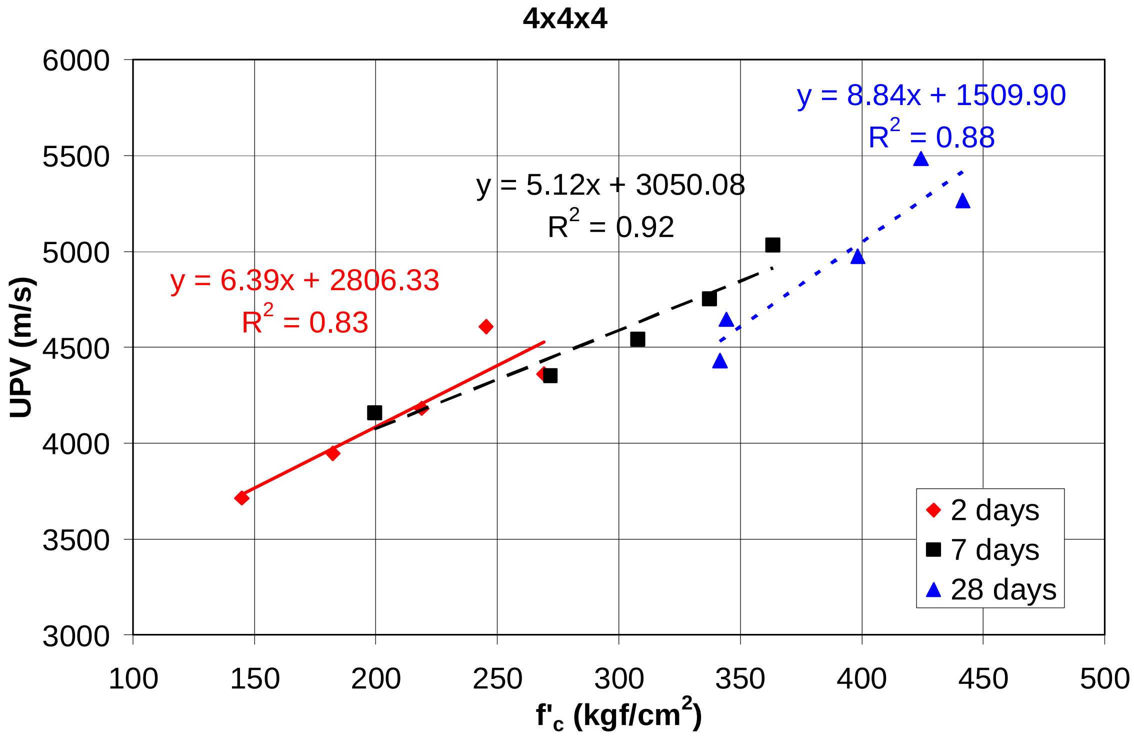


Figure 4. Relation between Compressive Strength and UPV

There are several studies examining the relation between UPV and compressive strength of concrete, and such a relation for mortar has not yet been made. In those studies, the relation between compressive strength and UPV of concrete is often considered as exponential $f = ae^{-bv}$ [8, 9]. However, in this study, it was seen that a linear relationship between the UPV and compressive strength of mortar seems to best represent the data as presented in Figure 4. The graph in the figure was obtained for the two types of specimens, 4x4x4 and 5x5x5 cubical specimens, respectively. As seen from the two graphs the relation between compressive strength and UPV also changes with age. This was also mentioned by Sturrup et. al., as they concluded that a pulse velocity/compressive strength relationship developed at early ages is not applicable at later ages, and this relationship will be complicated by the presence of cracks or voids in the concrete due to improper consolidation [10].

4. CONCLUSIONS

The following conclusions could be made as a result of this experimental study:

- When the effect of specimen geometry on the UPV of mortars were considered, it was observed that as the path length increases there is a significant decrease in the measured UPV. This is attributed to the attenuation of ultrasonic waves in the cement mortar.

- In ASTM D 2845 (pulse velocity testing of rocks), it is recommended that the minimum lateral dimension of the test specimen should be at least five times greater than the wavelength of the traversed wave. However, in ASTM C 597 (pulse velocity testing of concrete) that requirement is only one. As a result of this study, it can be concluded that, for cement mortars, as the traversed length (L or D) to wavelength (λ) ratio, L/λ or D/λ increases the results of the UPV test becomes more reliable, and the use of a 150 kHz transducer on a 4 or 5 cm length mortar specimen becomes more reliable as the wavelengths produced by the 150 kHz are, almost, three times smaller when compared to the 54kHz transducers.

- The linear relationship that exists between the compressive strength and UPV changes, as the age of mortar increases. This relationship will be complicated by the presence of cracks and voids in the mortar due to improper consolidation.

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